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Interrelationship between nutrients and chlorophyll-a in an urban stormwater lake during the ice-covered period

* **Kejian Chu** [1], **Yuntong She** [2], **Jeff Kemp** [3], **Mark Loewen** [4], **Evan Davies** [5]

[1] College of Environment, Hohai University, Nanjing, P. R. China

[1, 2, 3, 4, 5] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada

[1] E mail: kejian@ualberta.ca , [2] E mail: yuntong.she@ualberta.ca

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ABSTRACT

Urban stormwater lakes in cold regions are ice-covered for substantial parts of the winter. It has long been considered that the ice-covered period is the "dormant season," during which ecological processes are inactive. However, little is known about this period due to the historical focus on the open-water season. Recent pioneering research on ice-covered natural lakes has suggested that some critical ecological processes play out on the ice. The objective of this study was to investigate the active processes in ice-covered stormwater lakes. Data collected during a two-year field measurement program at a stormwater lake located in Edmonton, Alberta, Canada were analyzed. The lake was covered by ice from November to mid-April of the following year. The mean value of chlorophyll-a during the ice-covered period was 22.09% of the mean value for the open-water season, suggesting that primary productivity under ice can be important. Nitrogen and phosphorus were remarkably higher during the ice-covered period, while dissolved organic carbon showed little seasonal variation. Under ice-covered conditions, the total phosphorus was the major nutrient controlling the ratio of total nitrogen to total phosphorus, and a significant positive correlation existed between total phosphorus and chlorophyll-a when the ratio was smaller than 10. The results provide preliminary evidence of the critical nutrient processes in the Stormwater Lake during the ice-covered period.

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1. Introduction

Stormwater lakes support urban runoff management and prevent flooding and downstream erosion in urban areas. In cold regions, these lakes are ice-covered for substantial part or the entire winter. It has long been considered that the ice-covered period is the "dormant season" for lakes (Hampton et al., 2015), during which ecosystems subjected to low temperatures are "on hold" and most ecological processes are inactive until the environmental conditions become more conducive to the growth of aquatic organisms (Bertilsson et al., 2013). In the original Plankton Ecology Group's (PEG) model (an influential freshwater

***Corresponding Author:**
College of Environment, Hohai University, Nanjing, P. R. China
E-mail address: kejian@ualberta.ca

ecological model), the ice-covered period is described as a physical suppressor of the ecosystem and essentially a "reset" button for renewal in the following spring (Sommer et al., 1986). From this perspective, most historical research had focused on the open-water period as the "growing" season, and few studies have included winter research on ice-covered lakes; thus, little is known about the physics, geochemistry, and biology under ice in these systems (Hampton et al., 2017).

More recently, some pioneering winter lake research has shown increasing evidence that some critical ecological processes are playing out under the ice (Salonen et al. 2009, Bertilsson et al., 2013). For example in Lake Erie, the under-ice phytoplankton growth and loss rates in mid-winter were found to be as high as those of the summer months (Twiss et al., 2014). Lenard and Wojciechowska (2013) compared the phytoplankton community composition of two lakes in two consecutive winters. Both lakes favored the development of nanoplankton when they were ice covered in one winter, but produced microplankton when they were completely ice-free in the second winter. Phytoplankton community structure was found to be strongly correlated with ice thickness (Ozkundakci et al., 2016). High species diversity has been found under ice despite unfavorable conditions, including limited light availability, low water temperatures, restricted air-water gas exchange and prevention of wind-induced mixing (Salonen et al., 2009, Schröder, 2013). The concentration of nutrients and dissolved organic carbon may help to drive the plankton dynamics (Babanazarova et al., 2013). Griffiths et al. (2017) examined the shifts in diatom assemblages from ten High Arctic lakes, lakes and concluded that ice cover is likely the principle driver of some of the most important ecological changes, resulting in increased diversity and the emergence of novel growth forms and epiphytic species. With respect to winter stormwater lakes, previous studies have mostly focused on the hydrodynamic, water quality, pollutant removal performances, and operational environmental risk (e.g., Marsalek et al., 2000, 2003; Semadeni-Davies, 2006; Tixier et al., 2012). However, ecological processes in ice-covered stormwater lakes have not received the same level of attention as the natural lakes.

The objective of this study was to investigate the active processes in an ice-covered stormwater lake. Data including concentrations of nutrients, dissolved carbon, and chlorophyll-a collected during a two-year field measurement program at a stormwater lake located in Edmonton, Alberta, Canada were analyzed. The Stormwater Lake was covered by ice from November to mid-April in the following year. The differences in concentrations of total nitrogen (TN), total phosphorus (TP), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and chlorophyll-a (Chl-a) between ice-covered and open-water seasons were explored. The correlations between these variables were analyzed using the Pearson correlation test and their correlative behaviors in ice-covered and open-water periods were compared to reveal the pattern of nutrient processes occurring under ice in the study lake.

2. Study Lake and methodology

The study Stormwater Lake is located in southwest Edmonton and has an average depth of 1.78 m and a storage volume of 39,000 m^3. The bathymetry of the lake together with the inlet and outlet locations are shown in Figure 1. A total of 162 water samples were collected during a two-year field measurement program between October 2013 and October 2015. Sampling locations were at the inlet and outlet locations, as well as at the corner and center of the lake. 26 samples were collected during the ice-covered period by drilling holes at monthly intervals. The water samples were sent to the Biogeochemical Analytical Service Laboratory (BASL) at the University of Alberta for measurement of the pertinent water quality parameters, including TN, TP, DOC, DIC, and Chl-a. TN and TP were analyzed by Lachat QuickChem QC8500 FIA Automated Ion Analyzer (American Water Works Association, 2004, 1999), DOC and DIC by Shimadzu TOC-5000A Total Organic Carbon Analyzer (EPA 415.1 (Modified)), and Chl-a by Shimadzu RF-1501 Spectrofluorophotometer (Welschmeyer, 1994) and Varian Cary 50 Probe UV-Visible Spectrophotometer (EPA 446.0 (Modified)). The detection limits of the BASL test results are 7 ppb for TN, 1.4 ppb for TP, 0.1 ppm for DOC, 0.2 ppm for DIC and 0.2 μg/L for Chl-a.

3. Results and discussion

The sampling results for TN, TP, DOC, DOC, and Chl-a in the stormwater lake are presented in Figure 2. Ice-covered periods are indicated by dashed rectangles. Descriptive statistics were calculated to describe the main characteristics of the variable measurements (Table 1). During the monitoring period, the concentrations of

DOC and DIC were relatively stable, with coefficients of variation of 24.41% and 31.80% respectively. Daily averages for the different sampling locations (± standard deviation) ranged from 4.92 ± 3.17 mg/L to 13.58 ± 0.67 mg/L for DOC and 10.89 ± 3.02 mg/L to 31.0 ± 0.93 mg/L for DIC. The concentrations of Chl-a, TN and TP fluctuated more, with corresponding coefficients of variation of 83.79%, 57.89%, and 65.48%, and daily averages ranging between 1.45 ± 1.09 µg/L and 300.9 ± 75.12 µg/L, 549.71 ± 16.71 µg/L and 3438.4 ± 897.19 µg/L, 89.4 ± 8.74 µg/L and 650.2 ± 321.99 µg/L respectively.

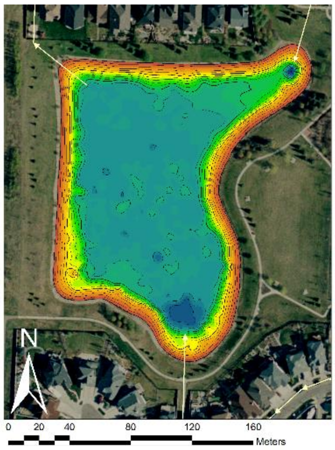
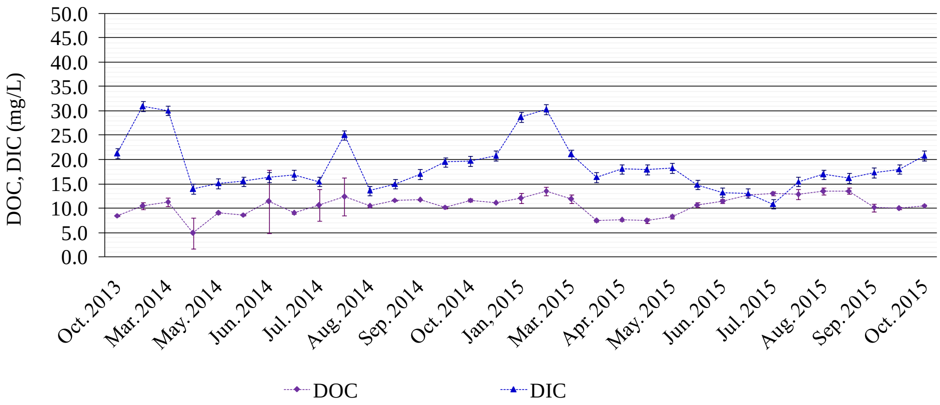


Figure 1. Bathymetry of the study Stormwater Lake, arrows indicate incoming and outgoing storm sewer.

a)



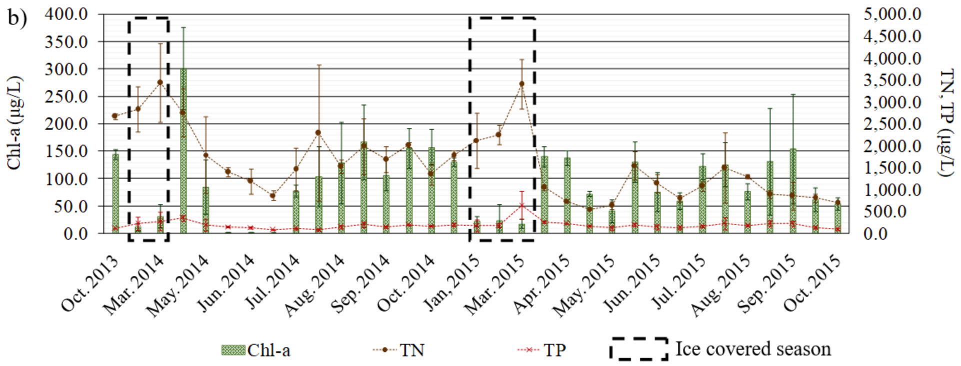


Figure 2. Measured concentration of a) DOC, DIC; b) Chl-a, TP, TN during the two-year monitoring period.

Table 1. Descriptive statistics of the measurements during the monitoring period.

Variable	Min	Max	Mean	SD	CV
Chl-a (µg/L)	1.45	300.90	87.59	73.39	83.79%
TN (µg/L)	549.71	3438.40	1518.67	879.10	57.89%
TP (µg/L)	89.40	650.20	194.82	127.56	65.48%
DOC (mg/L)	4.92	13.58	10.55	2.57	24.41%
DIC (mg/L)	10.89	31.00	18.34	5.83	31.80%

Notes: Min=minimum of daily average value of all sampling locations; Max=maximum of daily average value of all sampling locations; Mean=average value during monitoring period of all sampling locations; SD=standard deviation; CV=coefficient of variation.

Table 2 provides descriptive statistics for the measurements during the ice-covered and open-water seasons. The corresponding periods in both monitoring years were combined for this

analysis. Average Chl-a under ice-covered conditions (22.11 ± 17.48 μg/L) was significantly lower, but still approximately a quarter (22.09%) of the open-water average (100.1 ± 73.37 μg/L). Therefore, primary productivity under ice should be considered an important part of the whole-year productivity.

TN, TP and DIC were remarkably higher under ice-covered conditions (2788.31 ± 783.60 μg/L, 302.19 ± 247.79 μg/L and 28.34 ± 4.02 mg/L) compared to open-water conditions (1275.95 ± 661.92 μg/L, 174.29 ± 73.42 μg/L and 16.43 ± 3.83 mg/L), whereas DOC concentrations showed little seasonal variation (11.92 ± 1.34 mg/L under ice-covered condition and 10.29 ± 2.67 mg/L under open-water condition). The higher concentrations of TN and TP under the ice likely reflect nutrient input from the municipal storm sewer network, roadway and roadside deposit, deicing and anti-skid agents (Oberts et al., 2000), as well as leaf litter (Bratt et al., 2017). The seasonal difference was most prominent for TN, where the ratio of the under-ice average to the open-water average reached 2.19:1. This ratio was 1.73:1 for TP, 1.72:1 for DIC and 1.16:1 for DOC.

Table 2. Descriptive statistics for variable measurements under ice-covered and open-water conditions

		Chl-a (μg/L)	TN (μg/L)	TP (μg/L)	DOC (mg/L)	DIC (mg/L)
Ice-covered	Min	12.28	2124.00	186.60	10.50	21.06
	Max	32.23	3438.40	650.20	13.53	31.00
	Mean	22.11	2788.31	302.19	11.92	28.34
	SD	17.48	783.60	247.79	1.34	4.02
	CV	79.05%	28.10%	82.00%	11.23%	14.17%
Open water	Min	1.45	549.71	89.40	4.92	10.89
	Max	300.90	2763.33	349.67	13.58	25.05
	Mean	100.10	1275.95	174.29	10.29	16.43
	SD	73.37	661.92	73.42	2.67	3.83
	CV	73.30%	51.88%	42.12%	25.98%	23.30%

The correlation coefficient values among TN, TP, DOC, DIC and Chl-a are presented in Table 3. There were significant positive relationships between TN and TP under ice-covered (0.59, $p<0.01$) and open-water conditions (0.42, $p<0.01$). This suggests that both nutrients have the same input sources and outputs to the water area. During the ice-covered period, significant negative correlations existed between DOC and TN (-0.53, $p<0.01$), and DIC and TP (-0.58, $p<0.01$), whereas these correlations were very weak under open-water conditions. No statistically significant correlations were found among DOC, DIC and Chl-a under both ice-covered and open-water conditions. Chl-a appeared to vary independently from dissolved carbon during the monitoring period in the study lake.

A significant correlation existed between TP and Chl-a (0.68, $p<0.01$) as well as TN and Chl-a (0.50, $p<0.01$) during the open-water periods, while both nutrients were statistically uncorrelated to Chl-a under ice (-0.26, $p=0.20$ for TN; -0.13, $p=0.53$ for TP). The interaction patterns of nutrients with Chl-a differ between ice-covered and open-water conditions in the study lake. Under open-water conditions, TP had a stronger positive correlation with Chl-a than TN, indicating that TP plays a more important role in algal growth. The relationship between TP and Chl-a, shown in Figure 3 on a log-log scale, demonstrates a predominantly positive trend. Under ice-covered conditions, the overall weak relationships of TN and TP to Chl-a suggest that the stormwater lake is not primarily nutrient limited.

Table 3. Pearson's correlation among the measured variables for the study lake.

		TN	TP	DOC	DIC	Chl-a
Ice-covered	TN	1	0.59**	-0.53**	-0.43*	-0.26
	TP		1	-0.38	-0.58**	-0.13
	DOC			1	-0.06	0.34
	DIC				1	0.09
	Chl-a					1
Open water	TN	1.00	0.42**	-0.11	0.18*	0.50**
	TP		1.00	-0.22*	-0.04	0.68**

DOC	1.00	-0.06	-0.16
DIC		1.00	-0.14
Chl-a			1

Note: * significant (two-tailed) at p≤0.05 level; ** significant (two-tailed) at p≤0.01 level.

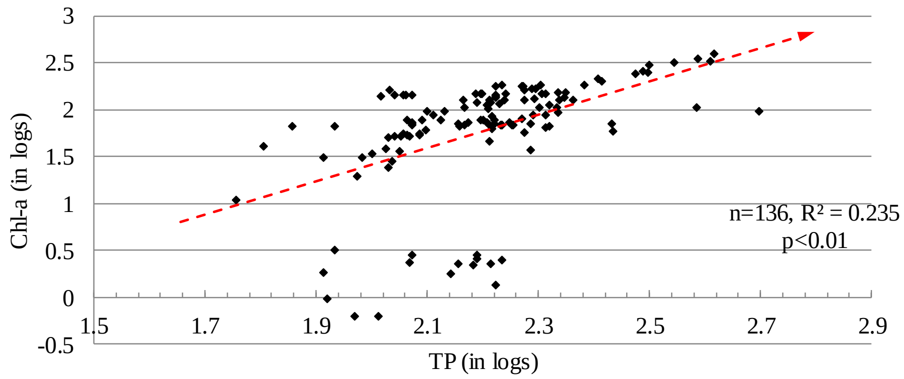


Figure 3. Log (TP) vs. Log (Chl-a) under open-water conditions.

For the study lake, the value of TN/TP was calculated to range from 2.64 to 24.62 under ice-covered conditions and from 2.31 to 47.08 under open-water conditions respectively. TP and TN/TP were more significantly correlated than TN and TN/TP under ice, but the opposite was found during the open-water period (Figure 4). This indicates that the major nutrient controlling the TN/TP level is TP during the ice-covered period, and it shifts to TN in the open-water seasons.

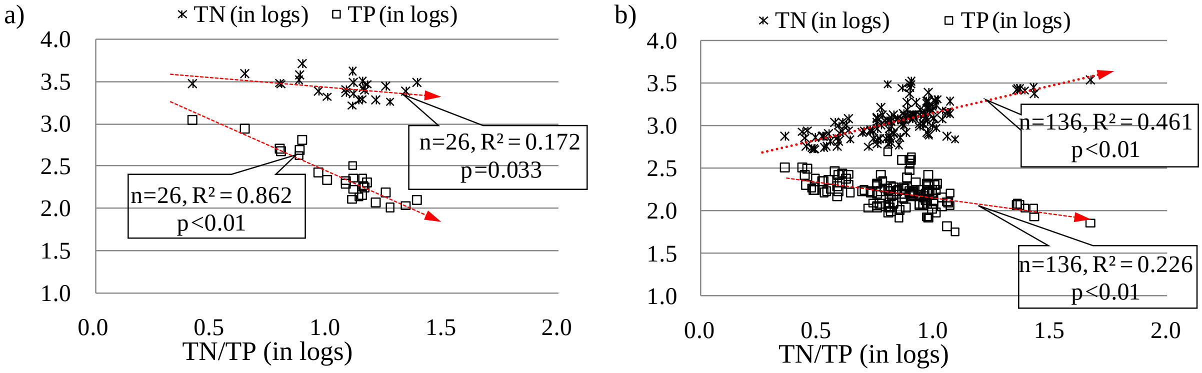


Figure 4. Log (TN/TP) vs. Log (TN) and Log (TP) under a) ice-covered conditions; b) open-water conditions.

Generally, a lake is considered nitrogen-limited when TN/TP < 10; nitrogen- or phosphorus-limited or phosphorus-limited when TN/TP > 10. The relationships between TN, TP and Chl-a at different TN/TP levels are presented in Figure 5. Significant positive correlations existed between TP and Chl-a under both ice-covered conditions (0.73, $p<0.05$) and open-water conditions (0.73, $p<0.01$) when TN/TP<10. The Chl-a concentration increased dramatically with respect to the TP concentration under open-water conditions, and gradually under ice. When TN/TP>10, TP was positively related to Chl-a under open-water conditions (0.58, $p<0.01$), but the correlation was non-significant during the ice-covered period (0.26, $p=0.30$). The correlations between TN and Chl-a were significantly positive in open-water season (0.55, $p<0.01$ when TN/TP<10; 0.56, $p<0.05$ when TN/TP>10); however, during the ice-covered period, the situation differed strongly: when TN/TP<10, TN had a non-significant negative correlation with Chl-a (-0.37, $p=0.36$); when TN/TP>10, the relationship was very weak (-0.002, $p=0.99$).

a)

b)

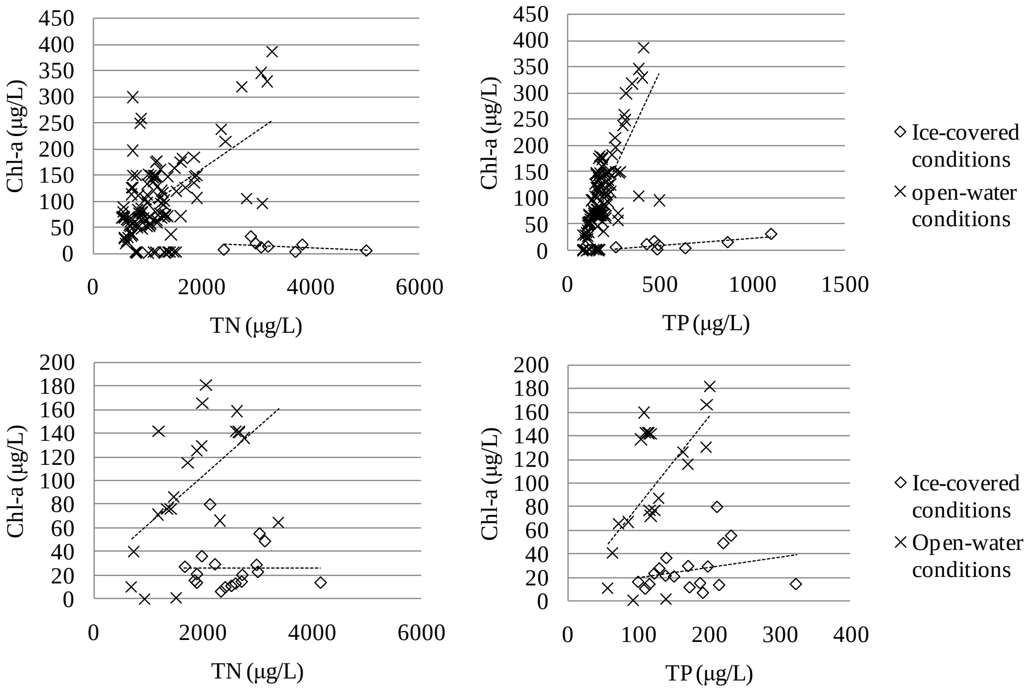


Figure 5. Relationships between TN, TP and Chl-a at a) TN/TP < 10; b) TN/TP > 10

4. Conclusion

The nutrient processes in a study stormwater lake were investigated. Data analyzed included the concentrations of TN, TP, DOC, DIC, and Chl-a collected during a two-year field measurement program. The Stormwater Lake was covered by ice from November to mid-April in the following year for both winters, allowing a comparison between ice-covered and open-water conditions. The results indicated that the mean value of Chl-a under ice-covered condition was 22.09% of the mean value under open-water conditions, suggesting the potential importance of primary productivity under ice. Concentrations of TN, TP, and DIC were remarkably higher under ice-covered conditions, while DOC showed little seasonal variation. The correlation trends of nutrients with Chl-a also varied seasonally. TP was found to be more determinative of Chl-a concentrations in open-water season. During the ice-covered period, TP was the major nutrient controlling the ratio of TN to TP, and the relationships between nutrients and Chl-a were remarkably different under different TN/TP.

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